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MONTEREY, CALIFORNIA

THESIS

MEASURING THE EFFECTIVENESS OF WEAPONS SYSTEMS IN TERMS OF SYSTEM ATTRIBUTES

by

Kevin W. Brown

December 1995

Principal Advisor: Robert E. Ball

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In this thesis, the relationship between the characteristics or attributes of a military weapon system (e.g., speed, reliability, survivability) and the effectiveness of that system is thoroughly examined. Success in system acquisition relies on (1) the early identification and successful incorporation of those system attributes that are critical to system effectiveness, and (2) the specification of numerical values for the system attributes (the system requirements) that maximizes system effectiveness at an acceptable cost. New definitions for system, system attributes, and system effectiveness, as well as relevant DoDI 5000.2 guidance are provided. In addition to the currently-mandated battle level at which system effectiveness should be measured (in terms of engagement or battle outcomes), the author uses a wide spectrum of system acquisition-related literature to advocate that system effectiveness should also be measured at the mission level (in terms of mission outcome). Several existing mathematical models which combine a few key system attribute measurements into single-number measures of system effectiveness in accomplishing a particular mission are described. Then, the author proposes a hierarchy or tree which relates many system attributes to the four key attributes, Availability, Reliability, Survivability, and Capability, and hence to system effectiveness in accomplishing a specified mission.

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MEASURING THE EFFECTIVENESS OF WEAPONS SYSTEMS IN TERMS OF SYSTEM ATTRIBUTES

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Submitted in partial fulfillment
of the requirements for the degree of

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from the

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In this thesis, the relationship between the characteristics or attributes of a military weapon system (e.g., speed, reliability, survivability) and the effectiveness of that system is thoroughly examined. Success in system acquisition relies on (1) the early identification and successful incorporation of those system attributes that are critical to system effectiveness, and (2) the specification of numerical values for the system attributes (the system requirements) that maximizes system effectiveness at an acceptable cost. New definitions for system, system attributes, and system effectiveness, as well as relevant DoDI 5000.2 guidance are provided. In addition to the currently-mandated battle level at which system effectiveness should be measured (in terms of engagement or battle outcomes), the author uses a wide spectrum of system acquisition-related literature to advocate that system effectiveness should also be measured at the mission level (in terms of mission outcome). Several existing mathematical models which combine a few key system attribute measurements into single-number measures of system effectiveness in accomplishing a particular mission are described. Then, the author proposes a hierarchy or tree which relates many system attributes to the four key attributes, Availability, Reliability, Survivability, and Capability, and hence to system effectiveness in accomplishing a specified mission.

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I. INTRODUCTION

A. PURPOSE

The purpose of this thesis is to examine the relationship between the characteristics or attributes of a military weapon system and the effectiveness of the system. System effectiveness is widely viewed as the result of the complex interaction of a multitude of system attributes, such as lethality, reliability, survivability, and maintainability. The only given official guidance for weapon system acquisition regarding system effectiveness measurement is that the measures of effectiveness (MOEs) should measure operational capabilities in terms of engagement or battle outcomes. Because the official guidance does not provide a standard model for system effectiveness measurement, several models have been offered which reduce the measurement of system effectiveness to an equation involving the combination of a few key attribute measurements, or performance parameters.

In this thesis, the author will propose a mission level for measuring system effectiveness, in addition to the battle level. Based on this alternative level, and a review of several existing system effectiveness models, the author will propose a hierarchy of system attributes which may affect overall system effectiveness in accomplishing a specified mission. Ultimately, this thesis should provide the reader with a better understanding of the relationship between system attributes and system effectiveness.

B. APPROACH

The author will accomplish the purpose described above through the following chapters. First, in Chapter II, a few key definitions and issues will be addressed. In Chapter III, the current system effectiveness measurement process, as defined in the

official U.S. Code and DoD guidance, will be presented. In Chapter IV, a mission level for measuring system effectiveness will be proposed which allows a linkage between system attributes and system effectiveness. In Chapter V, the relationship between system attributes and system effectiveness in the system design/test and evaluation processes will be examined. In Chapter VI, the quantification of system effectiveness will be examined, and two general methods of combining key system attributes into single-number system effectiveness measurements will be presented, along with several representative models. Lastly, in Chapter VII, the author will propose a hierarchy or tree of system attributes which may affect overall system effectiveness in accomplishing a specified mission.

C. SCOPE

This thesis is limited to the standard U.S. acquisition process for weapons systems which requires all of the DoD 5000-mandated documentation. It will not consider recent relaxations in documentation requirements for some minor systems. Because the DoD 5000 documents are currently being revised, those draft revisions that are pertinent to this thesis are included. As a further limitation, the included models and systems are only samples of a model population that cannot be fully included in one report. Therefore, there are undoubtedly some aspects of system effectiveness measurement which will not be covered. This thesis will, however, attempt to address many key areas which are applicable to the subject matter.

II. SYSTEMS, ATTRIBUTES, AND EFFECTIVENESS

A. INTRODUCTION

In this chapter, the author will provide some preliminary information and definitions as a foundation for the follow-on examination of system effectiveness concepts and measurements. First, some basic definitions for "system" and "system attributes" will be provided. Next, the author will preview the examination of system effectiveness by presenting a list of the key issues which will be addressed in this thesis.

B. KEY DEFINITIONS

1. System

A specific definition of what constitutes a system has yet to be universally accepted. Several different definitions of systems can be found in the system effectiveness-related literature. Three examples are:

> A set of interacting components composed of humans and machines (including software) directed toward performing a function or number of functions and operating within the constraints of time and specified environments. [Ref. 1:p. 6]

> A number of parts which are connected together in order to transform a given set of inputs into a given set of outputs. [Ref. 1:p. 81]

> A set of interrelated components which interact with one another in an organized fashion toward a common purpose. [Ref. 2:p. 3]

This thesis will focus on military weapon systems, which are defined by the author using a variation of the first definition given in this section:

"A set of interacting components composed of humans and machines assembled for the purpose of one or more military missions and operating within the constraints of time and specified environments."

2. System Attributes

As there is no universally-accepted definition for a system, there is also no universally-accepted term used to describe the attributes of a system. In this report, the author will combine the most commonly-used terms into the following definition for system attributes: "The characteristics, capabilities, or parameters of a system." Examples of some possible system attributes are shown in Table 2.1.

Speed	Survivability	Availability
Range	Susceptibility	Maintainability
Payload	Vulnerability	Logistic Supportability
Weight	Compatability	Manpower Supportability
Diameter	Human Factors	Transportability
Maneuverability	Safety	Reliability
Lethality	Interoperability	Natural Environmental Effects/Impacts

Table 2.1. Some Possible System Attributes

Note that many of the attributes listed in Table 2.1 can easily be quantified at the beginning of a system acquisition program using well established metrics. For example, the attributes of speed, range, and payload can have the metrics of kilometers/hour, kilometers, and kilograms, respectively. These quantifiable attributes of the developing or developed system can also be tested and evaluated relatively

easily because they are essentially deterministic in nature; that is, a relatively small number of non-destructive tests is sufficient to obtain an estimate of their value.

Other attributes, such as reliability, safety, and survivability, are more difficult to quantify at the beginning of system acquisition because of their random nature. For these attributes, probability measures, such as mean time between failures, probability of a mishap in 100,000 flight hours, and probability of mission survival, could be used as the defining metric. The testing required to determine these attributes is also more difficult because of the relatively large number of tests required to obtain an accurate estimate of their value. In addition, the system testing may be complicated by the destructive nature of the attribute in the event of failure, as in the case of safety and survivability.

A third type of attribute, such as interoperability and compatability, can not be quantified. These attributes are of a "yes or no" nature; either the system is interoperable or compatible with another system in one aspect or another, or it is not. However, even with these attributes, there may be other attributes that, when quantified, will result in a positive yes. For example, a radio being developed may be compatible with an existing radio if the frequency bands, which are quantifiable, are the same.

The crux of a successful system acquisition program is (1) early identification and successful incorporation of those attributes that are critical to system effectiveness and (2) the specification of numerical values for the system attributes (the system requirements) that maximizes system effectiveness at an acceptable cost.

3. Summary

Usage of the term, "attribute", in this report is a conscious attempt at uniformity. In the official DoD guidance (excerpts of which will be included in the next chapter), a variety of different terms are used to signify system attributes. These

terms are "characteristic," "capability" and "parameter," and they are usually preceded by the term "performance". Intermingled use of these different terms tends to complicate system-related discussion. In contrast to the official guidance, this report will replace these various terms with a single, overarching term, "attribute". This consistency should facilitate the reader's understanding of the subject matter.

C. SYSTEM EFFECTIVENESS - KEY ISSUES

1. System Effectiveness - A Complex Topic

In the system acquisition process, the effectiveness and the cost of a system are the two key ingredients in determining overall system value to the military services. Of these two key ingredients, system effectiveness is the one most difficult to define, explain, and measure. For instance, while system cost may be defined in terms of dollars, system effectiveness has no such standard basis for definition. Due to its inherent complexity, the topic of system effectiveness has received wide attention, and debate, throughout the DoD in recent years. In the current era of DoD downsizing and reduced budgets, the ability to relate the cost of a system to an associated, and appropriate, measure of effectiveness will become increasingly important.

2. The Key Issues

In this report, the author will attempt to add to the system effectiveness-related body of knowledge by addressing the following key issues:

1. "What is system effectiveness?"

2. "How is system effectiveness measured or quantified?"

3. "What are the levels at which system effectiveness should be measured?"

4. "How are system attributes measured?"

5. "What are some possible system effectiveness models, or hierarchies, which link system attribute metrics to system effectiveness measurement?"

As a prelude to later examination of these key issues, the next chapter will present applicable excerpts from the official guidance related to system effectiveness in the system acquisition process.

III. THE OFFICIAL GUIDANCE

A. INTRODUCTION

This chapter will present the applicable guidance related to the topic of system effectiveness, as found in the current DoD 5000 series instructions and the U.S. Code, Title 10. Measures of effectiveness (MOEs), along with measures of performance (MOPs), schedule, and cost, are developed during the system acquisition process and are described in several key documents. The chapter will begin with a brief overview of the system acquisition process, followed by a detailed description of the pertinent information included in the key documents. The Marine Corps Predator Short Range Assault Weapon (SRAW) and Advanced Amphibious Assault Vehicle (AAAV) systems will be used as examples throughout the chapter.

B. THE SYSTEM ACQUISITION PROCESS - AN OVERVIEW

The five major milestone decision points and the five phases of the system acquisition process, illustrated in Figure 3.1, provide the basis for comprehensive management and progressive decisionmaking associated with program maturation. The process begins with the development of the Mission Need Statement (MNS). Milestone 0, Concept Studies Approval, marks the initial formal interface between the system requirements generation and subsequent system acquisition management processes. Milestone 1 marks the official start of a new system-related acquisition program. Subsequent phases and milestone decision points facilitate the orderly translation of broadly stated mission needs into system attribute requirements and a stable design that can be produced efficiently.

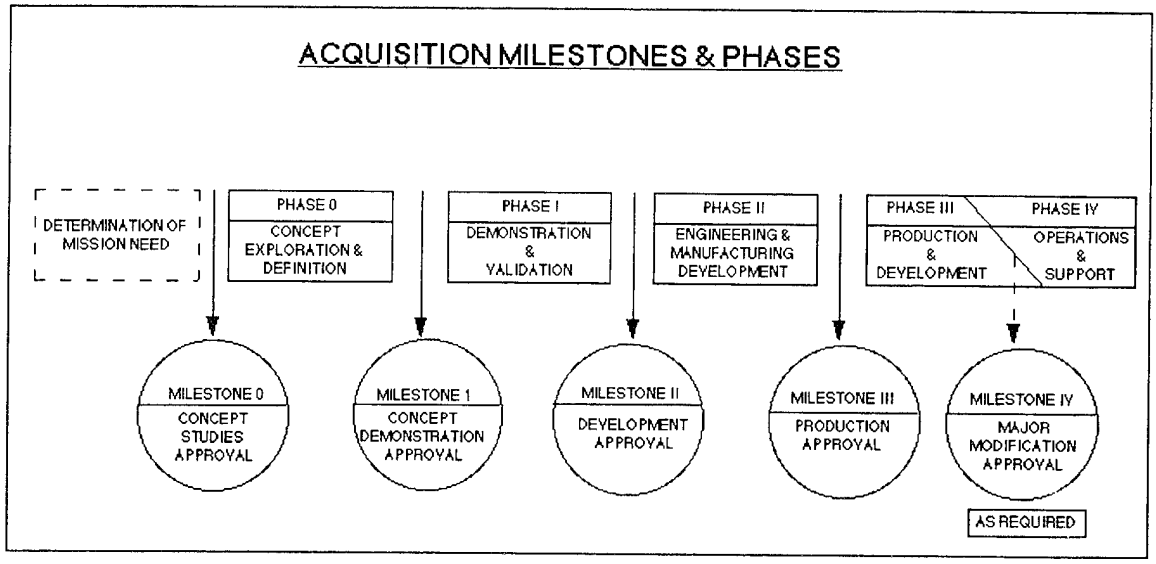

Figure 3.1. Acquisition Milestones & Phases

C. THE KEY DOCUMENTS AND THEIR RELATED OUTPUTS

The key documents in the system acquisition process are the Mission Need Statement (MNS), the Cost and Operational Effectiveness Analyses (COEA), the Operational Requirements Document (ORD), the Test and Evaluation Master Plan (TEMP), and the Acquisition Program Baseline (APB). Using actual examples from the Marine Corps Predator SRAW system, Table 3.1 provides an overview of the primary outputs of these documents. With the exception of the MNS, these documents require updating through the system acquisition process as the system evolves from a concept to a final end product.

DOCUMENT	OUTPUT	EXAMPLE (PREDATOR)
MNS	Desired Operational Capabilities	The System must be capable of being fired safely from enclosed areas such as buildings or bunkers.
COEA	Functional Objectives (FOs)	System must defeat tanks and armored vehicles equipped with explosive reactive armor.
	Measures of Effectiveness (MOEs)	Percent Enemy Armored Fighting Vehicles Destroyed.
	Measures of Performance (MOPs)	Must have a range of at least 600m.
ORD	Performance Parameters	Warhead must be capable of meeting the threshold target-defeat criteria against a Soviet T-80 MBT with ERA.
	Logistics and Readiness Requirements	Predator will consist of a launcher and missile as a singular unit for issue. The launcher will be considered a disposable item upon firing of the missile.
	Critical System Characteristics (CSCs)	The system must be capable of operating properly in all battefield environments with its only limitation being the capabilities of the current crew-served night vision sight.
TEMP	Critical Operational Issues (COIs)	Will the system enhance the chances of survivability of Marines firing it in comparison to the current light antiarmor system?
	Minimum Acceptable Operational Performance Requirements (MAOPRs)	System will be man-portable, not to exceed 20 lbs in weight and 40 inches in length.
	Critical Technical Parameters (CTPs)	Accuracy for stationary target > $.5P_h$ at 600m.
APB	Key Performance Parameters (KPPs)	Stationary Target P_h Threshold .5 at 600m/Objective .8 at 600m.

Table 3.1. The Key Documents and Their Primary Outputs [Ref. 3]

D. THE MISSION NEED STATEMENT (MNS)

The system acquisition process begins with the development of a mission need statement (MNS) by the user or operating command. To assist the reader's understanding of the DoD guidance concerning the MNS, definitions and examples of "operational scenario" and "mission" are given below:

1. Operational Scenario

Operational scenarios are realistic descriptions of potential wartime operations. An example of an operational scenario, from the AAAV Supplemental Analysis, is provided:

> This scenario included two Marine Expeditionary Forces (MEF), one ashore and one afloat. In a coordinated counteroffensive, the land-based MEF attacks northwest, while the afloat MEF lands north of the Orange (enemy) forces. The concept is to trap and neutralize the enemy units between the two MEFs. Early in the counterattack, the following preparatory actions were taken:
>
> - A Blue Regiment conducted a heliborne assault to remove an artillery threat to two Littoral Penetration Sites (LPS) selected for the surface assault.
>
> - A Marine Infantry Regiment and an Artillery Battalion were inserted vertically and established an inland fire base to support the surface assault.
>
> - A Marine Infantry Regiment landed vertically, west of the Littoral Penetration Zone (LPZ) and established blocking positions to facilitate a surface assault by the afloat Regimental Landing Team (RLT).
>
> Continuing with the scenario, a surface amphibious assault begins approximately one hour after blocking positions were established by the vertical assault. A Marine RLT afloat, which consists of 4,500 Marines, is tasked to conduct a night surface assault across two designated beaches and maneuver to rapidly seize an inland town. The RLT will then establish blocking positions in the vicinity of the town to trap Orange forces attempting escape to the northwest. [Ref. 4:pp. iv-v]

2. Mission and Mission Tasks

A mission is an operational task performed by military personnel and/or military systems as part of an operational scenario. Most missions can be sub-divided into measurable mission tasks or functional objectives. For example, the aforementioned RLT mission of trapping Orange forces consists of several mission tasks, some of which relate directly to the AAAV, such as the ship-to-shore movement of 4,500 Marines across two designated beaches in a night assault.

3. The DoD Guidance

The DoD guidance concerning the MNS states:

> *1.* ***Mission***. Identify and describe the mission need or deficiency. Define the need in terms of mission, objectives, and general capabilities. Do not discuss the need in terms of specific equipment or system-specific performance characteristics.
>
> *2.* ***Constraints.*** Describe, as applicable, key boundary conditions related to infrastructure support that may impact on satisfying the need; logistics support; transportation; mapping; charting and geodosy support; manpower; personnel; and training constraints; command, control, communications, and intelligence interfaces; security; and standardization or interoperability within the North Atlantic Treaty Organization (NATO) or with other allies or DoD Components. Address the operational environments (including conventional; initial nuclear weapons effects; nuclear, biological, and chemical contamination (NBCC); electronic; and natural) in which the mission is expected to be accomplished. Define the level of desired mission capability in these environments. [Ref. 5:p. 2-1-1]

E. THE COST AND OPERATIONAL EFFECTIVENESS ANALYSIS (COEA)

Based on the MNS, a cost and operational effectiveness analysis (COEA) is developed for several alternative concepts. The COEA is the most important document in the system effectiveness measurement process. As part of the COEA, mission needs are sub-divided into functional objectives (mission tasks). Also, alternative system concepts which fulfill the desired mission need are compared using Measures of Effectiveness (MOEs) and Measures of Performance (MOPs). The DoD guidance concerning the COEA states:

1. COEAs aid decision making by illuminating the relative advantages and disadvantages of the alternatives being considered and showing the sensitivity of each alternatives to possible changes in key assumptions (e.g., the threat) or variables (e.g., selected performance capabilities). Accordingly, the analysis takes the form of a problem of choice. The COEA should aid decisionmakers in judging whether or not any of the proposed alternatives to the current program (i.e., the status quo) offer sufficient military benefit to be worth the cost.

2. The COEA will typically draw on several sub-analyses. These include analyses of mission needs, the threat and U.S. capabilities, the interrelationship of systems, the contribution of multi-role systems, measures of effectiveness, costs, and cost-effectiveness comparisons.

3. Functional Objectives (FOs). Statements describing, in quantitative terms, the tasks a system needs to perform in accomplishing the mission(s). They depend on the type of system at issue. For example, when analyzing transportation systems, functional objectives are stated in movement requirements. For firepower systems, they reflect the types of targets to be engaged. The effectiveness of system alternatives is the direct result of the degree to which the functional objectives are attained. [Ref. 5:pp. 8-4 and 8-5]

4. Measures of Effectiveness (MOEs). To judge whether an alternative is worthwhile, one must first determine what it takes to make a difference. **Measures of effectiveness should be defined to measure operational capabilities in terms of engagement or battle outcomes.**

5. Measures of Performance (MOPs). Measures of performance, such as weight and speed, should relate to the measures of effectiveness such that the effect of a change in the measure of performance can be related to a change in the measure of effectiveness. [Ref. 6:pp. 4-E-1 - 4-E-3]

F. THE OPERATIONAL REQUIREMENTS DOCUMENT (ORD)

Based on the initial COEA, an Operational Requirements Document (ORD) is developed. The ORD translates the COEA FOs/MOEs/MOPs into system-specific operational requirements. Thus, the ORD defines the system attribute requirements, or performance parameters necessary to bring about the overall system effectiveness defined in the COEA. To assist the reader's understanding of the DoD guidance concerning the ORD, the DoD definition of performance parameter is provided:

1. Performance Parameter

Those operational and support characteristics of a specific system that allow it to effectively and efficiently perform its assigned mission over time. The support characteristics of the system include both support-ability aspects of design and the support elements necessary for system operation. [Ref. 6:p. 15-13]

2. The DoD Guidance

The DoD guidance concerning the format for the ORD states:

a. Capabilities Required

Identify performance capabilities and characteristics required. State in operational terms and prioritize if possible. Specify each performance parameter in terms of a minimum acceptable value (threshold) required to satisfy the mission need and a performance objective. The objective should represent a measurable, beneficial increase in capability or operations and support above the threshold.

(1) ***System Performance.*** Include system performance parameters such as range, accuracy, payload, speed, mission reliability, etc. Describe mission scenarios (wartime and peacetime, if different in terms of mission profiles, employment tactics, and environmental conditions (all inclusive; natural and man-made, e.g., weather, countermeasures, ocean acoustics, etc).

(2) ***Logistics and Readiness.*** (These are measures related to system supportability). Include measures of mission-capable rate, operational availability, frequency and duration of preventive or scheduled maintenance actions, etc. Describe in terms of mission requirements considering both wartime and peacetime logistics operations. Identify combat support require-ments including battle assessment damage repair capability, mobility requirements, expected maintenance manpower and skill levels, and surge and mobilization objectives and capabilities. [Ref. 5:pp. 3-1-1 - 3-1-2]

(3) ***Critical System Characteristics.*** (These are) those design features that determine how well the proposed concept or system will function in its intended environment. Critical system characteristics include survivability, transportability, energy efficiency, and interoperability, standardization, and compatibility with other forces and systems including support infrastructure. [Ref. 6:p. 4-C-1]

Address electronic counter countermeasures (ECCM) and Wartime Reserve Modes (WARM) requirements; conventional, initial nuclear weapons effects, and nuclear, biological, and chemical contamination (NBCC), survivability; natural environmental factors (such as climatic, terrain, and oceanographic factors); and electromagnetic compatibility and frequency spectrum assignment for systems operating in the

electromagnetic spectrum. Define the expected mission capability (e.g., full, percent degraded, etc) in the various environments. Include applicable safety parameters such as those related to system, nuclear, explosive, and flight safety. Identify communications, information, and physical and operational security needs. [Ref. 5:p. 3-1-2]

G. THE TEST AND EVALUATION MASTER PLAN (TEMP)

The TEMP identifies the necessary operational test and evaluation (OT&E) activities and translates the COEA and ORD effectiveness and performance requirements into testable parameters. To assist the reader's understanding of the DoD guidance concerning the TEMP, definitions for "operational effectiveness" and "operational suitability", along with the U.S. Code, Title 10 guidance concerning operational testing, are provided:

1. **Operational Effectiveness.** The overall degree of mission accomplishment of a system when used by representative personnel in the environment planned or expected (e.g., natural, electronic, threat etc.) for operational employment of the system considering organization, doctrine, tactics, survivability, vulnerability, and threat (including countermeasures, initial nuclear weapons effects, nuclear, biological, and chemical contamination (NBCC) threats).

2. **Operational Suitability**. The degree to which a system can be placed satisfactorily in field use with consideration given to availability, compatibility, transportability, interoperability, reliability, wartime usage rates, maintainability, safety, human factors, manpower supportability, logistic supportability, natural environmental effects, documentation, and training. [Ref. 6:p. 15-13]

3. **U.S. Code, Title 10 Guidance.** (The term "operational test and evaluation" means) the field test, under realistic combat conditions, of any item of (or key component of) weapons,

equipment, or munitions for the purpose of determining the effectiveness and suitability of the weapons, equipment, or munitions for use in combat by typical military users. [Ref. 7:p. 400]

4. **The DoD Guidance**. The DoD guidance concerning the TEMP format states:

a. Critical Operational Issues

(1) List in this section the critical operational issues. Critical operational issues are the operational effectiveness and operational suitability issues (not parameters, objectives, or thresholds) that must be examined in operational test and evaluation to evaluate/assess the system's capability to perform its mission....

(2) If every critical operational issue is resolved favorably, the system should be operationally effective and operationally suitable when employed in its intended environment by typical users. [Ref. 5:pp. 7-1-2 and 7-1-3]

(a) ***Minimum Acceptable Operational Performance Requirements***. Reference the Operational Requirements Document and summarize the critical operational effectiveness and suitability parameters and constraints (manpower, personnel, training, software, computer resources, transportation (lift), and etc.) described therein.

(b) ***Critical Technical Parameters***. List in matrix format the critical technical parameters of the system (including software maturity and performance measures) that have been evaluated or will be evaluated during the remaining phases of developmental testing. Critical technical parameters are derived from the Operational Requirements Document, critical system characteristics, and technical performance measures and should include the parameters in the acquisition program baseline.

Next to each technical parameter, list the accompanying objectives and thresholds... [Ref. 5:pp. 7-1-3]

H. THE ACQUISITION PROGRAM BASELINE (APB)

The APB is the program manager's tool for monitoring system development and for identifying key cost, schedule, and performance parameters for Milestone decision making. Key performance parameters are found in the Performance Baseline of the APB. To assist the reader's understanding of the DoD guidance concerning the performance portion of the APB, definitions for "key performance parameters", "thresholds", and "objectives", and an example of key performance parameters for a particular system, the AAAV(F), are provided:

1. **Key Performance Parameters**. "Those system-related parameters that if the thresholds are not met, the milestone decision authority would require a reevaluation of alternative concepts or design approaches" [Ref. 6:p. 11-A-1-1]

2. **Thresholds**. "Thresholds are the minimum acceptable value required to satisfy the mission need." [Ref. 6:p. 4-B-1]

3. **Objectives**. Objectives are also provided for key parameters, and are defined as a "measurable, beneficial increase in capability or operations support above the threshold." [Ref. 5:p. 3-1-1]

4. **Key Performance Parameters - Example.**

Table 3.2 shows the key performance parameters from the AAAV(F) Acquisition Program Baseline, with related system attributes provided by the author.

KEY PERFORMANCE PARAMETER	OBJECTIVE/THRESHOLD	RELATED SYSTEM ATTRIBUTE
High Water Speed (knots)	25/20	Speed
Forward Speed on a Hard Surface Road (k/h)	72/69	Speed
Carrying Capacity (Marines)	18/17	Payload
Firepower (Maximum Effective Range)	2000/1500	Lethality
Armor Protection Against (millimeter/meter)	(30/1000)/(14.5/300)	Survivability
Mean Time Between Critical Mission Failure (hrs) (MTBCMF)	95/70	Reliability

Table 3.2. AAAV(F) Key Performance Parameters [Ref. 8]

5. **The DoD guidance.** The DoD guidance concerning the performance baseline portion of APB states:

   a. The Performance Baseline

Each commodity has a few parameters which are critical to that commodity and must be addressed (e.g., aircraft weight, missile range, reliability). List these key critical parameters.... Enter acquisition program baseline performance requirements for parameters tailored to each program. Performance objectives and thresholds will be derived from the Operational Requirements Document and the results of the previous acquisition phase. Performance objectives and thresholds must be reviewed by the Joint Requirements Oversight Council (for acquisition category I D programs) at each milestone, and ultimately be verifiable by developmental and operational testing. Performance includes operational, technical, and supportability parameters. [Ref. 5:pp. 14-1-3 and 14-1-7]

I. THE NEW DRAFT DODI 5000.2 GUIDANCE

As of October 1995, an updated revision of the DoDI 5000.2 has been issued for review by the DoD community. In this revision, which has not yet been formally approved, the guidance concerning the aforementioned key documents does not significantly change, except for the guidance concerning the COEA. The new draft DoDI 5000.2 replaces the current term "COEA" with the term "Analysis of Alternatives", along with the following, significantly less specific guidance:

> ...These analyses are intended to aid and Document Decisionmaking by illuminating the relative advantages and disadvantages of the alternatives being considered. Show the sensitivity of each alternative to possible changes in key assumptions (e.g., threat) or variables (e.g., selected performance capabilities). The analysis shall aid decision-makers in judging whether or not any of the proposed alternatives to an existing system offer sufficient military benefit to be worth the cost. There shall be a clear linkage between the analysis of alternatives, and requirements, and system evaluation measures of effectiveness. [Ref. 9:p. 2.2]

The reader should be aware that this change, if ultimately accepted, may affect some of the information in this thesis. However, since the updated guidance has not been formally approved, the author will base this thesis on the existing DoDI 5000.2 guidance.

J. SUMMARY OF OFFICIAL GUIDANCE

The MNS, COEA, ORD, TEMP, and APB are the key documents used in developing systems in response to mission needs. It is important to note that the COEA, ORD, TEMP, and APB are not static documents, but are updated throughout the system development process as the system is developed in greater detail. The

provided excerpts from the official guidance establish a basis for further examination of system effectiveness measurement and its relation to measures of system attributes.

K. BEYOND THE OFFICIAL GUIDANCE

Despite the detailed information provided in this chapter, there are certain aspects of system effectiveness which require further clarification. Specifically, the official guidance inadequately addresses the levels at which system effectiveness can be measured, the definition of system effectiveness, the measurement of system attributes, and possible models/hierarchies for linking measures of system attributes to measures of system effectiveness.

The remainder of this thesis will provide information related to these missing aspects of system effectiveness guidance. In the next chapter, the author will offer a alternative viewpoint to the official guidance concerning the level(s) at which system effectiveness should be measured, which will then be incorporated into a definition for system effectiveness. In the remaining chapters, some various models/hierarchies for linking measures of system attributes to measures of system effectiveness will be offered.

IV. SYSTEM EFFECTIVENESS - TWO LEVELS

A. INTRODUCTION

In the previous chapter, the current official guidance concerning system effectiveness stated that measures of effectiveness (MOEs) must be made in terms of engagement or battle outcome (e.g., loss-exchange ratios, residual force ratios, etc.). In this chapter, the author will provide an additional viewpoint, that system effectiveness should also be measured in terms of mission accomplishment (e.g., capability to accomplish logistic resupply operations, capability to accomplish TRAP operations). This additional viewpoint will be shown to be consistent with 1) the DoD guidance concerning the Concept Exploration and Definition (CE/D) Phase, 2) the Operational Test and Evaluation (OT&E) process, and 3) Army and Marine Corps guidance. Furthermore, excerpts from the Medium Lift Replacement (MLR) study, in which the MV-22 was chosen over alternative systems, will show that mission-level MOEs are already in use. Finally, an argument will be made that measuring system effectiveness at the mission level, in addition to the battle level, provides a better opportunity for system development and test personnel to link system attributes to system effectiveness.

B. THE OFFICIAL GUIDANCE - MEASURES OF EFFECTIVENESS

The official guidance concerning measures of effectiveness, given in Chapter III and shown below, specifies only one level at which system effectiveness should be measured.

> To judge whether or not an alternative is worthwhile, one must first determine what it takes to make a difference. **Measures of effectiveness should be defined to measure operational capabilities in terms of engagement or battle outcomes.** [Ref. 6:p. 4-E-3]

The following sections will demonstrate that MOEs should also be defined in terms of mission outcomes.

C. THE CONCEPT EXPLORATION AND DEFINITION (CE/D) PHASE

1. The Official Guidance

In contrast to the current battle-level MOE guidance, other guidance concerning the CE/D Phase leads to an additional viewpoint as to the level at which system effectiveness can be measured. The following excerpts, which were excluded from the previous chapter due to their inapplicability to a particular key document, support this argument:

> a. Milestone 0, Concept Studies Approval, marks the initial formal interface between the requirements generation and acquisition management systems. As a result of this review (in the CE/D Phase), **studies are conducted of materiel concepts to identify the most promising potential solution(s) to validated mission needs.**
>
> b. Subsequent phases and milestone decision points facilitate the orderly **translation of broadly stated mission needs** into system specific performance requirements and a stable design that can be produced efficiently. [Ref. 6: pp. 2-1 and 2-2]

2. Two Levels for Measurement

a. Two Levels for Measuring System Effectiveness

From the MOE guidance and CE/D phase guidance, one can arrive at two possible levels for measuring system effectiveness. On the one hand, the MOE guidance, "measures of effectiveness should be defined to measure operational capabilities in terms of **engagement or battle outcomes**", leads to the conclusion that

system effectiveness must be measured at the battle level. On the other hand, the CE/D phase guidance, "studies are conducted of materiel concepts to identify the most promising potential solution(s) to validated **mission needs**", and "translation of broadly stated **mission needs**", leads to the conclusion that system effectiveness should also be measured in terms of mission accomplishment, at the mission level.

b. Mission Needs

Now, there would be no inconsistency between these two levels if mission needs were stated explicitly in terms of desired engagement or battle outcomes. However, this is usually not the case. The following excerpts from the official guidance concerning the mission need statement (MNS) support this argument:

> *(1)* ***Mission.*** Identify and describe the mission need or deficiency. Define the need in terms of **mission, objectives, and general capabilities**. Do not discuss the need in terms of specific equipment or system-specific performance characteristics.
>
> *(2)* ***Constraints.*** Describe, as applicable, key boundary conditions related to infrastructure support that may impact on satisfying the need; logistics support; transportation; mapping; charting and geodosy support; manpower; personnel; and training constraints; command, control, communications, and intelligence interfaces; security; and standardization or interoperability within the North Atlantic Treaty Organization (NATO) or with other allies or DoD Components. Address the operational environments (including conventional; initial nuclear weapons effects; nuclear, biological, and chemical contamina-tion (NBCC); electronic; and natural) in which the mission is expected to be accomplished. Define the level of **desired mission capability** in these environments. [Ref. 5:p. 2-1-1)

3. Summary

Since mission need statements are expressed in terms of operational capabilities required to conduct missions (at the mission level), the search for system solutions to those needs requires measuring the effectiveness of alternative systems at both the battle **and** mission level. For some major systems, such as an aircraft carrier, mission accomplishment might best be stated as an engagement or battle outcome. However, for most systems, which operate at a lower level, mission accomplishment is an essential intermediate step that combines with a multitude of other factors to ultimately result in an engagement or battle outcome.

D. THE OPERATIONAL TEST AND EVALUATION (OT&E) PROCESS

1. The DoD Guidance

Measuring system effectiveness at the mission level is also consistent with the guidance concerning the Operational Test and Evaluation process. The following excerpts from the official guidance support this argument:

> The term "**operational** test and evaluation" means "the field test, under realistic combat conditions, of any item of (or key component of) weapons, equipment, or munitions for the purpose of determining the **effectiveness** and suitability of the weapons, equipment, or munitions for use in combat by typical military users. [Ref. 7:p. 400]

> **Operational Effectiveness. The overall degree of mission accomplishment** of a system when used by representative personnel in the environment planned or expected (e.g., natural, electronic, threat etc.) for operational employment of the system considering organization, doctrine, tactics, survivability, vulnerability, and threat (including countermeasures, initial nuclear weapons effects, nuclear, biological, and chemical contamination (NBCC) threats). [Ref. 6:p. 15-13]

2. Two Levels

As in the earlier section, one could argue that the level for measuring operational effectiveness (mission accomplishment) is usually different than the currently-mandated level for measures of effectiveness (engagements or battle outcomes).

3. The Commander, OT&E Draft "Battle Outcome" MOEs Letter

The following excerpt from a draft letter dated 22 February 1994, from the Commander of the Navy's operational test and evaluation force, highlights some serious problems related to the current guidance concerning the battle level for MOEs:

> OSD/DOT&E are interpreting DODINST 5000.2 requirements for linkage of COEA MOEs to operational testing and the use of battle outcome MOEs with such rigidity that I believe this causes a significant threat to all Navy oversight programs. The problem with this approach is that a requirement to use high-level MOEs, for many systems, obscures real effectiveness and suitability defining measures. This could lead directly to poor acquisition decisions.
>
> The current OSD/DOT&E philosophy is that all systems can and must be tested in terms of "outcome of the battle" MOEs, and that all these MOEs must be thresholded. I do not believe this is a sound policy for now or in the future. Most of the systems we test will not determine the outcome of a battle and they are only one contributor among a number of powerful factors which will determine the outcome of an engagement....
>
> The less influence a system exerts on the outcome of the battle, the more obscure the effectiveness and suitability of these systems in high-level MOEs become.... The current trend of overemphasis on battle outcome level MOEs and the strict requirement for their linkage will directly lead to unsatisfactory results; important acquisition decisions will be based on inappropriate parameters; and the cost of testing will increase because battle outcome MOEs will require considerably more

> testing than necessary to isolate the system's true effectiveness.... I believe we should not transfer this problem to the future. Now is the time for a solution.... The goal for the long-term and short-term approach is to ensure testable, measurable, and meaningful MOEs are used to evaluate a weapon system's worth. [Ref. 10:pp. 1-2]

4. Summary

The operational test community would benefit from allowing the measurement of system effectiveness at both the battle and mission levels. One can derive from the Commander, OT&E letter that, for many systems which do not contribute directly to a battle-level outcome, mission-level MOEs may provide a better indication of a system's true effectiveness and suitability.

E. ARMY AND MARINE CORPS GUIDANCE

1. The Guidance

A primary source of guidance used by the Army and the Marine Corps for measuring system effectiveness is the TRADOC PAM 11-8, "Operational Effectiveness". The following excerpts support the measurement of system effectiveness at the mission level.

> Effectiveness is the degree (or measure) to which a system performs its **stated mission**. The system is effective if it does what **the requirement** specifies.... An MOE is a quantitative indicator of the ability of a system to accomplish its **designated task**. [Ref. 11:p. 12]

2. Summary

Thus, the argument for measuring system effectiveness at the mission level is enhanced by the TRADOC guidance. In reference to system effectiveness, the publication uses the terms "stated mission", "the requirement", and "designated task".

These are obviously not references to some battle outcome, but are rather references to specific mission accomplishment.

F. THE MEDIUM LIFT REPLACEMENT (MLR) STUDY

1. Background

In the Medium Lift Replacement (MLR) study, or Cost and Operational Effectiveness Analysis (COEA) [Ref. 12], dated 24 August 1994, the MLR aircraft included the MV-22 Osprey and various helicopters. Using the terms "operational" and "tactical", the MLR study compared the alternative aircraft at the battle and mission levels. Applicable excerpts from the study are given below.

2. The Operational Level

Table 4.1 shows the primary level MOEs at the operational (battle) level.

MOE 1-1	Contributions of the MLR alternatives to "WIN QUICKLY"
MOE 1-2	Contributions of the MLR alternatives to "WIN DECISIVELY"
MOE 1-3	Contributions of the MLR alternatives to "DOMINATE BATTLESPACE"
MOE 1-4	Contributions of the MLR alternatives to "MINIMIZE CASUALTIES"
MOE 1-5	Contributions of the MLR alternatives to "GENERATE OVERWHELMING TEMPO"

Table 4.1. MLR Study - Primary Operational (Battle) Level MOEs

At this level, the contributions of the MLR aircraft to joint operations and the power projection capabilities of Naval Expeditionary Forces (NEF) were evaluated. The focus was on the effects the fleets of different MLR aircraft have on the battle outcomes of the Blue and Orange forces. The MOEs were stated in the tenets of

Operational Maneuver From the Sea (OMFTS). The battle was represented by two operational situations (OPSITS) modeled in the Corps Battle Analyzer (CORBAN). The distinguishing input was the different mission completion times that the different MLR aircraft fleets had on force buildup during assault operations. In addition to the primary level MOEs, there were 23 other secondary level MOEs such as orange battalions neutralized, loss-exchange ratios, etc.

3. The Tactical Level

Table 4.2 shows the primary MOEs at the tactical (mission) level.

MOE 2-1	Capability of MLR alternatives to build up forces
MOE 2-2	Survivability of MLR alternatives
MOE 3-1	Capability of MLR alternatives to accomplish logistics resupply operations
MOE 3-2	Capability of MLR alternatives to accomplish MEDEVAC operations
MOE 3-3	Capability of MLR alternatives to accomplish TRAP operations
MOE 3-4	Capability of MLR alternatives to accomplish SAR operations

Table 4.2. MLR Study Primary Tactical (Mission) Level MOEs

On the tactical level, the effects of the MLR alternatives on a variety of missions were evaluated. At this level, the MOEs focused on the effects the fleets of different MLR aircraft had on force-buildup rates, logistics resupply operations, medevac operations, TRAP operations, and SAR operations. Additionally, an MOE specifically related to survivability was used. In the evaluation of force buildup rates and logistics resupply missions, three tactical situations (TACSITs) modeled in the Amphibious Assault Model (AAM) were used. The primary inputs for the AAM were system attributes such as aircraft speed, altitude, range, payload, fuel

expenditure, reliability, maintainability, and availability. For the remaining MOEs, spreadsheet models were used, all with system attributes as inputs. In addition to the primary level MOEs, there were 11 other secondary level MOEs such as TRAP completion time, medevac lives saved, etc.

4. Summary

One can see that system effectiveness for the MLR study was measured at both the battle (operational) and mission (tactical) levels. At the battle level, the CORBAN model used one primary input, mission completion time, to produce 28 operational level MOEs. These MOEs were used to show the degree of effectiveness that the V-22, the system with the shortest mission completion time, had over the other systems at the battle level. At the mission level, numerous system attributes were used as inputs to the various models. Seventeen MOEs were used to show the degree of effectiveness that the V-22, due to its superior performance capabilities, had over competing systems at the mission level.

G. SYSTEM DESIGN AND TEST

In a further argument for mission-level MOEs, system engineers do not usually develop systems with an engagement or battle outcome in mind. They develop systems to meet specific mission-related requirements. Thus, an effectiveness threshold for time to move Marines from ship-to-shore gives the engineer a basis upon which to develop requirements for system attributes such as speed and carrying capacity. Likewise, test and evaluation personnel do not usually test systems to meet certain engagement or battle outcome objectives. They test systems to see if desired system attribute requirements are met and if the system meets specific mission requirements. Although battle-level MOEs are useful in determining how systems will affect the outcome of the battle, mission-level MOEs provide a better basis upon which to design and test systems.

H. AN IMPORTANT CONCLUSION

All of the above analyses lead to an important conclusion. **System effectiveness should be measured at the mission level, in terms of mission tasks (i.e., broad operational capabilities), in addition to the battle level, in terms of engagement or battle outcomes.** For instance, one measure of effectiveness for comparing the V-22 to alternative systems could be stated in terms of mission completion time to move a MEF-sized assault element from ship-to-shore. Obviously, the system which accomplishes this mission in the shortest amount of time, without an unacceptable number of casualties, will be the more effective system in meeting that particular mission need. Stating this effectiveness in battle-related terms may or may not be reasonable, depending on the relation of the system's mission to battle-level outcomes. As shown in the MLR study, battle-level effectiveness measures for major systems like the MV-22 may be derived using models based on mission-level effectiveness measures, such as mission completion time.

V. THE SYSTEM DEVELOPMENT PROCESS

A. INTRODUCTION

The military services develop and employ systems in order to accomplish their assigned missions. In the system development process, the measurement of system effectiveness is used, along with the associated cost, to choose between competing system designs. Thus, the measurement of system effectiveness is a key element of the system acquisition process.

Previous chapters described the current system effectiveness and performance (attribute) measurement process, and established that system effectiveness should be measured at both the battle and mission levels. This chapter will provide a definition for system effectiveness and a deeper review of the concept of system effectiveness, with emphasis on the relationship between system attributes, system design, and system effectiveness at the mission level. A discussion of system design and operational test and evaluation considerations will be included. Following chapters will focus on possible models for linking system attributes to quantify measures of effectiveness at the mission level.

B. SYSTEM EFFECTIVENESS DEFINED

Based on the previous chapters, definitions for system effectiveness and measure of effectiveness are now proposed:

System Effectiveness. The ability of a system to accomplish a mission, and achieve a favorable battle outcome, in an optimum manner.

Measure of Effectiveness. An outcome-oriented measure of a system's effectiveness.

The measurement of system effectiveness may be a relative, not absolute, measure of a system's utility compared to other systems. However, once a particular

system concept has been chosen for development, system effectiveness must be translated into absolute threshold values that provide a basis upon which system attribute specifications can be developed. Using this definition of system effectiveness, this chapter will provide a more in-depth discussion of how system effectiveness measurement at the mission level relates to the overall system design process.

C. THE CHALLENGE OF SYSTEM DESIGN

1. Relationship Between System Attributes and System Effectiveness

Depending on the system, there are many system attributes which can potentially contribute to system effectiveness. Keeping in mind the required relationship between measures of performance (attributes) and measures of effectiveness, the challenge of system design is to link the measures of the many system attributes to system effectiveness. This is accomplished through the use of tradeoff analyses.

2. Tradeoff Analyses

The current official guidance concerning tradeoff analyses (with the term "attribute" inserted as applicable) states:

a. Tradeoff Analyses

> They (tradeoff analyses) display the implications of "trading" one set of controllable variables (such as system attribute measurements) for another (such as cost).... To do a tradeoff analysis, one must identify areas of uncertainty, conduct sensitivity analyses, and establish thresholds.
>
> *(1)* ***Uncertainty.*** Tradeoff analyses identify areas of uncertainty and estimate their extent. The implications of the uncertainties are examined in cost models and effectiveness models. This serves to highlight for decision makers the areas in which uncertainties most affect the analysis and, therefore, its results.

(2) ***Sensitivity***. Sensitivity analyses show explicitly how military utility is affected by changes in system attributes. They show how system attributes (size, weight, etc.) drive performance, and how performance affects military utility or effectiveness. Parameters should be varied individually where it is reasonable to do so. The uncertainty inherent in estimating attributes and in determining their impact should be portrayed explicitly.

(a) As a result of this step, the analysis is able to show "where we are on the curve": whether the desired performance is stretching the system to the point that increases in performance add little of benefit; whether the results are sensitive to change.

(b) In a very real sense, there are few "hard, unchallengeable" requirements in weapons acquisition. Certain attributes and levels of effectiveness are not "essential, regardless of cost." Sensitivity analysis illuminates how important it is to incorporate these features into a system.

(3) ***Thresholds***. An important step in developing a cost and operational effectiveness analysis is to determine thresholds, the maximum cost or minimum acceptable performance that could be tolerated in a system. In order to approach thresholds and acceptability thresholds reasonably, senior decision makers and users must be directly involved in reviewing the combinations of cost and performance that would be acceptable.

(a) Cost thresholds are expressions of value. They answer questions such as: How valuable is a given capability to the Service? How much would a Service be willing to give up in order to obtain that capability? At what point would it be preferable to drop the idea in favor of some other course of action?

(b) Performance thresholds may be more difficult to determine but are at least as important as cost thresholds. They show at what point degradations in performance yield outcomes that no longer satisfy the mission need. Together, cost and performance thresholds help in determining which alternatives are worthwhile and

what combinations or intervals of performance and cost are acceptable. [Ref. 5:pp. 8-10 and 8-11]

3. Optimal System Design

As stated earlier, system effectiveness measurement at the mission level provides the most direct means of linking system attributes to system effectiveness. Once threshold (minimum acceptable) values for system effectiveness at the mission level have been identified, system engineers are faced with determining the optimal combination of system attribute specifications (stated as thresholds and objectives) that will result in an overall effective, and affordable, system. Since most systems are built to accomplish multiple missions, and most missions involve numerous mission tasks (functional objectives), this presents a dilemma for the system designer. Based on user input regarding the relative importance of all system MOEs to overall system effectiveness, the designer determines certain system attributes which become key design objectives to which the designer optimizes the overall system design.

D. RELATING MOES TO TEST AND EVALUATION OF MOPS

1. Operational Test and Evaluation

Once the engineers have developed thresholds and objectives for system attributes, the system is built to the desired specifications. Once built, the system must be tested and evaluated in a realistic operational setting to ensure that the system attribute specifications are achieved. Also at this stage, the attributes should be reevaluated in terms of their impact on desired system effectiveness, as reflected by the COEA MOEs.

2. The 1992 USD(A) Memorandum

The importance of relating measures of effectiveness to the test and evaluation of system attributes was reemphasized in a 1992 Memorandum from the Under

Secretary of Defense for Acquisition [Ref. 13]. A summary of the guidance (with the term "attribute" inserted where applicable) found in that memorandum is included in this section.

a. The Documents

(1) The Cost and Operational Effectiveness Analysis (COEA). The DoD component, in the process of performing a Milestone I COEA, should identify the MOEs to be used in the COEA and show how these MOEs are derived from the Mission Need Statement (MNS). Each COEA should include MOEs reflecting operational utility that can be tested. For those MOEs that cannot be directly tested, the COEA should show how changes in testable attributes or MOPs can be related to changes in COEA MOEs.

(2) The Operational Requirements Document (ORD). The MOEs and related MOPs should be included in the ORD.

(3) The Acquisition Program Baseline (APB). The key MOEs and MOPs should also be included in the APB subject to review by the Requirements Validation Authority and approval by the Milestone Decision Authority.

(4) Test and Evaluation Master Plan (TEMP). The TEMP should document how the COEA MOEs and related MOPs will be addressed in the test and evaluation of the selected alternative system.

b. Linking MOEs to Test Results

The Milestone Decision Authority and the Requirements Validation Authority should be able to review the COEA using test results to reaffirm the decision that the selected alternative is an effective approach to satisfying an operational requirement. If the system effectiveness (MOE) thresholds stipulated in the APB and ORD and used in the COEA are not supported by test results, the COEA

sensitivity analyses should be available to assist in determining whether the system, as tested, still offers sufficient military benefit to be worth its cost and whether the system can be confirmed to be operational effective and operationally suitable.

E. SYSTEM EFFECTIVENESS MODELS

The necessity for measuring system effectiveness in terms that can be linked to system attributes has led to the development of several system effectiveness models. These models measure system effectiveness in terms of mission accomplishment and provide frameworks for linking system attributes to system effectiveness. In the next chapter, several of these models will be presented.

VI. SEVERAL SYSTEM EFFECTIVENESS MODELS

A. INTRODUCTION

Ultimately, the developer must determine the individual and combined effects of all system attributes when choosing between alternative systems or system designs. In Chapter IV, the author proposed that system effectiveness be measured at both the mission and battle levels. Of these two levels, the mission level provides the most direct means for relating system attributes to system effectiveness. This argument is supported by the abundance of models which link system attributes to system effectiveness at the mission level, and the lack of models which link these attributes to system effectiveness at the battle level. This chapter will describe several existing models which relate mission-level measures of effectiveness to combinations of key system attributes.

These models will be sub-divided into two categories, multiplicative and additive. The multiplicative models are the Weapons Systems Effectiveness Industry Advisory Committee (WSEIAC), Habayeb, Ball, OPNAVINST 3000.12, Marshall, and Giordano models. Only one additive model, the Georgia Tech Aerospace Systems Design Laboratory (ASDL) model, will be described.

B. MULTIPLICATIVE VERSUS ADDITIVE MODELS

All of the listed models develop mission-specific measures of effectiveness through the combination of a few key system attributes into mathematical equations involving attribute measures. There are two basic types of these equations. The first, more popular, method involves the multiplication of key attribute measures, leading to a single overall measure of effectiveness. The second method involves applying weighting coefficients to various key attribute measures which reflect the relative

importance of those attributes, and then adding the weighted attribute value, leading to a single overall measure of effectiveness.

C. THE MULTIPLICATIVE MODELS

The multiplicative models which follow are based on the premise that a system's effectiveness in accomplishing a particular mission is a product of a few key system attributes. These attribute measures are expressed as probabilities, and they all must be present, in some degree, for a system to be considered effective. The most effective system, using these models, is the one with the highest probability of mission accomplishment over time.

1. The WSEIAC Model

a. The Equation

In the final Weapons System Effectiveness Industry Advisory Committee (WSEIAC) report of January 1965, an equation identifying three key system attributes, Availability (A), Dependability (D), and Capability (C), was presented for overall system effectiveness (E) evaluation:

$$\mathbf{E = [A] * [D] * [C]}$$

$$= [a1\ a2\ \ldots.an] \begin{bmatrix} d11\ d12\ldots.d1n \\ d21\ldots\ldots\ldots d2n \\ dn1\ldots\ldots\ldots dnn \end{bmatrix} \begin{bmatrix} c1 \\ c2 \\ cn \end{bmatrix}$$

where **[E]** is the measure of the extent to which a system can be expected to achieve a set of specific mission requirements and is a function of availability, dependability, and capability.

b. Definitions of Key Attributes

(1) Availability. **[A]** is an availability row matrix, which presents the possible states of system condition at the start of the mission and is a function of the relationships among hardware, personnel, and procedures.

(2) Dependability. **[D]** is a dependability square matrix, which presents the probability that the system (1) will enter and/or occupy any one of its significant states during the specific mission, and (2) will perform the functions associated with those states.

(3) Capability. **[C]** is a capability column matrix, which presents the ability of the system to achieve the mission objectives; given the system condition(s) during the mission, and specifically accounts for the performance spectrum of the system.

c. Analysis

This model relies on a single-mission scenario. For the overall mission envelope, each possible system state is described and a matrix developed giving transition probabilities between states. The product of the three matrices is equal to overall system effectiveness. Judgement plays an integral part in arriving at capability values as well as in the development of the overall operational scenario for which the dependability matrix is set up.

2. The HABAYEB Model

a. The Equation

Dr. A. R. Habayeb, the technology manager for weapons command and control in NAVAIR's Weapons Division (AIR-912), in his book entitled *System Effectiveness* [Ref. 14], proposes an equation identifying three key system attributes, readiness (sr), reliability (r), and design adequacy (da). He places these attributes into an analytical structure using a probabilistic notion of system effectiveness (se),

Pse = Psr * Pr * Pda

where **Pse** is the probability that the system is effective.

b. Definitions of Key Attributes

(1) Readiness (Psr). The probability, that, at any point in time, the total system is ready to be operated on demand and operates satisfactorily when used under specific conditions.

(2) Reliability (Pr). The probability that the system will operate under stated conditions without malfunction for the duration of the mission, in other words, the mission reliability of the system.

(3) Design Adequacy (Pda). The probability that the system will successfully accomplish its mission, given that it is operated within design specification. It is the measure for performance capability.

c. Hierarchy of Attributes

As shown in Table 6.1, Habayeb offers a hierarchy in which lower-level attributes are listed below his three key attributes:

Readiness	**Reliability**	**Design Adequacy**
Transportability	Reliability	Survivability
Reliability	Durability	Vulnerability
Availability	Quality	Operational Suitability
Supportability		Interoperability
Maintainability		Compatibility
Quality		Durability
		Quality

Table 6.1. Habayeb's Hierarchy of System Attributes

d. Analysis

Habayeb's equation relies on a single-mission scenario. His three key attributes are interdependent operationally, and overall system effectiveness requires they all occur. The attributes are usually quantified independently of each other, in steps at different times. Design adequacy (capability) is initially built into the system, and is fixed until changes occur in the environment, e.g., new application or threat. Therefore, design adequacy is initially quantified at the early stages of system development, determined by simulation or experimentally, while assuming readiness and reliability events occur as specified.

Reliability is built into the system as it is developed and is quantified upon development of a system block diagram, parts counts of the system, and the failure rates of the hardware. Degradation in reliability is a function of time and the environment and assumes design adequacy and readiness are as specified.

Lastly, readiness presents procedural (e.g., repair, maintenance and operational, logistics), and training events, and is estimated from the reliability assessment and the mean time to repair (MTTR), and assumes design adequacy is as specified. As a caveat, Habayeb states that some aspects of reliability (e.g., redundancy, hardware quality and testing) and readiness (e.g., modular design and human factors) can be accounted for in the early stages of design adequacy. System effectiveness quantification then becomes an iterative process, where operational feedback data is used to continually refine the quantification of the three key attributes.

In his book, Habayeb has developed a detailed statistical proof of his equation, which is beyond the scope of this thesis.

3. The BALL Model

a. The Equation

Professor Robert E. Ball, a faculty member of the Naval Postgraduate School Aeronautics and Astronautics Department, in his book, *The Fundamentals of Aircraft Combat Survivability Analysis and Design* [Ref. 15], proposes a measure of combat effectiveness of an available aircraft in a particular scenario as the measure of mission success (**MOMS**), which is given by

$$\mathbf{MOMS = MAM * S}$$

b. Definitions of Key Attributes

(1) ***Mission Attainment Measure (MAM).*** The mission attainment measure is the effectiveness (expressed as a range between 0 and 1) of the offensive capability of the aircraft.

(2) ***Survivability (S).*** The effectiveness (also expressed as a range between 0 and 1) of the defense capability of the aircraft, where

$$Ps = 1\text{-}Pk$$

where Ps = the probability of survival, and

$Pk = Ph*Pk/h$

Ph = the probability of hit (susceptibility) and

Pk/h = the probability of kill given a hit (vulnerability)

c. Analysis

The **MOMS** equation was solely intended to provide a simple measure of effectiveness for system operational performance in a combat environment and the

impact that survivability has upon mission success. Professor Ball uses his **MOMS** formula to illustrate the tradeoffs between **MAM** and **S**. For example, in many combat situations the **MAM** is intentionally reduced in order to increase the **S.** In these situations, the more survivable aircraft can possibly have a smaller **MOMS** per aircraft. This translates into a tradeoff between quality (less capability per aircraft) and quantity (more survivable aircraft) to achieve the same overall level of mission success.

4. The OPNAVINST 3000.12 Model

a. The Equation

The *OPNAVINST 3000.12, Operational Availability of Equipment and Weapons Systems* [Ref. 16], provides the following equation which provides the three key system attributes, Operational Capability, Operational Availability, and Operational Dependability, as key to determining system effectiveness (SE):

$$\mathbf{SE = Co * Ao * Do}$$

b. Definitions of Key Attributes

(1) ***Operational Capability (Co).*** Refers to the system's operating characteristics (range, payload, accuracy, and the resultant ability to counter the threat, in terms of probability of kill, exchange ratios, etc.

(2) ***Operational Availability (Ao).*** Probability that a system is ready to perform its specified function, in its specific operational environment, when called upon at a random point in time.

(3) ***Operational Dependability (Do).*** Probability that the system, if up at the beginning of the mission, will remain up throughout the mission. Also referred to as "mission reliability".

c. Analysis

The OPNAVINST 3000.12 relies on a single-mission scenario and is intended to highlight the importance of operational availability as a critical element of system effectiveness. Other than offering the equation, the instruction goes no further in addressing the interrelationships of the three key attributes and only offers sub-elements for operational availability. Given Ao sub-elements are reliability, maintainability, and logistics resources. The OPNAVINST does state that capability, availability, and dependability must be defined relative to the specific warfare environment and operating scenario envisioned or employed for a given system.

5. The MARSHALL Model

a. The Equation

John Marshall, retired Marine Corps colonel, and systems engineer in the Unmanned Air Vehicle (UAV) Project Office, Naval Air Warfare Center Aircraft Division (NAWCAD) in his *ESP Proposal* [Ref. 17], has proposed an equation based on those of Habayeb and Ball. Marshall combines the key system attributes, Operational Availability (Ao), Mission Reliability (Rm), Survivability (S), and Mission Attainment Measure (MAM), to develop a single measure of Effectiveness/ Suitability/ Performance (**ESP**) using the following equation for system effectiveness (SE):

$$\mathbf{ESP = SE = Ao * Rm * S * MAM}$$

b. Definitions of Key Attributes

*(1) **Operational Availability (Ao).*** (includes logistics readiness) The probability that a system will be available for use when required. Given by equation: [Total up time / (total up and down time)] or [# of ready systems

/ total # systems]. Use Inherent Availability (A_i) for unfielded systems. - readiness in terms of inherent design characteristics. Given by the equation: (MTBF) / (MTBF+MTTR).

(2) ***Mission Reliability (Rm)***. The probability that a system will perform mission essential functions for a period of time under the conditions stated in the mission profile. Given by the equation: $e^{(-T/MTBOMF)}$.

(3) ***Survivability (S)***. The capability of a system to avoid or withstand man-made hostile environments without suffering an abortive impairment of its ability to accomplish its designated mission. Same as Ball's equation: $(1-P_h*P_{k/h})$.

(4) ***Mission Attainment Measure (MAM)***. Mission effectiveness. Probability of performing the defined mission, given Ao, Rm, and S. This probability will be based on successive trials during applicable operational scenarios. Given by the equation (1 - error rate).

c. Analysis

The ESP model relies on a single-mission scenario. According to Marshall, the model provides a common systems evaluation framework for DoD; a quantifiable, synergistic means to define and evaluate total system effectiveness. The model relies on a cyclical view of system performance and the key attributes that affect performance. The ESP model does not obviate the need for detailed analysis, but rather, it incorporates detailed analyses into a meaningful top-level equation to be used by decision makers. This model will be used as the basis for developing a system attribute hierarchy in the next chapter.

6. The GIORDANO Model

a. The Basic Equation

Paul Giordano, Systems Effectiveness Branch Head of the U.S. Naval Applied Science Laboratory, in his 1966 report, *Predicting Systems Effectiveness* [Ref. 18], proposed the following system effectiveness (**E**) equation:

$$\mathbf{E} = \mathbf{P_c} * \mathbf{P_t}$$

b. Definitions of Key Attributes

(1) ***Performance Capability (P_c)*** . Giordano does not specifically provide a definition. However, his usage of the term corresponds with the description of operational capability given in the OPNAVINST model. Thus, performance capability refers to the system's operating characteristics (range, payload, accuracy) and the resultant ability to counter the threat, in terms of probability of kill, exchange ratios, etc.

(2) ***Time Dependency of Performance (P_t)***. Resource penalty parameters. Adds a time dimension to performance and allows all the "ilities" to be treated as modifiers of optimal performance.

c. Analysis of Basic Equation

Giordano's basic equation is designed for a single-mission scenario. According to Giordano, the program manager will build a system effectiveness model based on specific attribute requirements, based on factors related to mission accomplishment. The sequence of events is given below.

First, the mission is reduced to tasks, which, if accomplished, will give the program manager confidence of mission success. The task descriptions form the basis for Effectiveness Analysis. Next, attribute requirements are established that

allow successful task accomplishment. The attribute values are varied according to task requirements. Acceptable levels of attribute values then become measures for detailed analytical modeling to assess sensitivities to resources, failures, logistics, degradation, and time demands. The interplay of simulation and analytical modeling is used to set up and evaluate systems and specific designs within systems. Giordano sees his equation as a means of treating all chosen attributes in a unified fashion and treating resource penalty-related attributes as an integral part of overall system performance.

Giordano's envisions that the program manager should treat resource penalty attributes in three distinct ways. First, absolute limits, or "thresholds" are placed on some penalties, and treated as "go, no go" requirements. Second, the penalties are treated as design parameters and their impact is measured where possible as a change in the equation. Finally, the penalties are treated as quantitative attributes of a system in their own right and specific values are estimated.

This leads Giordano into a discussion of combining attributes into an overall equation. If one can put a relative value on the attributes, they can be combined into a figure of merit or measure of effectiveness. However, Giordano warns against combining data beyond the point where it causes loss of information at the expense of simplicity. This is due to the variability built into the analysis.

d. The Multimission Equation

Of all the multiplicative models, only Giordano discusses system effectiveness for multimission scenarios. Giordano expands his basic equation to portray a sample representation of system effectiveness for a large system in a multimission scenario as follows:

$$\mathbf{E = W(Pc*Pt)/LT, W(Pc*Pt)/CA, W(Pc*Pt)/MP, W(Pc*Pt)/CO}$$

where **LT** is Lead Time, **CA** is Acquisition Cost, **MP** is Manpower, **CO** is Ownership Cost, and **W** is a measure of mission worth.

e. Analysis of Multimission Equation

The factors **LT**, **CA**, **MP**, and **CO** are examples of potential modifiers of the basic equation. The factor **W** is used to allow additional variation where multi-missions are treated independently or combined. **W** allows iterative analysis per mission.

Note that one could translate Giordano's multi-mission equation into an additive equation, where the factor **W** can be used to separately weight single-mission measures, and then combine them into an overall measure of multimission system effectiveness.

D. THE ADDITIVE MODEL - ASDL

1. The Equation

Dr. D. N. Mavris and Mr. D. DeLaurentis from the Aerospace Systems Design Labaratory at the School of Aerospace Engineering, Georgia Institute of Technology, in their paper entitled *"An Integrated Approach to Military Aircraft Selection and Concept Evaluation"* [Ref. 19], presented an equation identifying five key attributes, Affordability, Survivability, Readiness, Capability, and Safety, which combine into a single, overall measure of an aircraft system effectiveness, or overall evaluation criterion (**OEC**):

$$\mathbf{OEC = a(/LCC/LCC_{BL}) + b(MCI/MCI_{BL}) + c(EAI/EAI_{BL}) + d(P_{surv}/P_{survBL}) + e(A_i/A_{iBL})}$$

where a through e are importance coefficients which sum to 1, **LCC** is Life Cycle Cost, **MCI** is Mission Capability Index, **EAI** is Engine Related Attrition Index, $\mathbf{P_{surv}}$ is a measure of Survivability, and $\mathbf{A_i}$ is Inherent Availability.

2. Definitions of Key Attributes

a. **Life Cycle Cost (LCC).** A overall measurement of Affordability, or the total cost to the government for acquisition, ownership, operation, and disposal of the system over its life cycle.

b. **Mission Capability Index (MCI).** A overall measurement of Capability, or the aircraft's ability to complete its mission (satisfy or exceed all mission requirements).

c. **Engine-Caused Attrition Index (EAI).** A overall measurement of Safety, or an estimation of the effect on peacetime attrition of engine induced Class-A failures based on total number of aircraft operated.

d. **Probability of Survival ($\mathbf{P_{surv}}$).** An overall measurement of Survivability, or an aircraft's ability to evade detection and avoid damage which would result in loss of vehicle.

e. **Inherent Availability ($\mathbf{A_i}$).** An overall measurement of Readiness, or the degree to which an item is in operable and committal state at the start of the mission when the mission is called for, at an unknown time.

3. Analysis

The ASDL equation relies on a single-mission scenario and is used as follows. In comparing the effectiveness of competing systems, one picks a system, assigns a value of "1" to all the factors of that system, and then describes competing systems relative to the base system. For example, if the baseline system A has a .90 survivability, then system B with a .45 survivability would be assigned a MOE for that factor of .5. Subsequently, a weighting coefficient is applied to survivability to

show how important it is to the customer. This is repeated for each attribute. Summation of the five weighted attributes into a top-level measure, as is shown in the ASDL equation, provides a comparison of an alternative system's overall effectiveness to the baseline system and is helpful in choosing between alternative systems.

One problem with the ASDL equation is the subjectivity associated with assigning weighting coefficients. As the coefficients are basically measures of human preferences, the resultant OEC becomes a measure of preference, rather than effectiveness. Depending on one's preferences, choices between systems may change. However, the system itself, and its ability to accomplish the mission, may remain the same. In fact, if one has a predisposed preference for one system over all the others, one may be able to manipulate the coefficients until the equation shows the preferred system to be the most effective. Thus, the objectivity of this model may be quite low.

E. SINGLE VERSUS MULTIPLE MISSIONS

For the most part, the above equations only provide a measurement of system effectiveness in accomplishing a specific mission in a given operational scenario. Furthermore, in order to use these equations, one must define mission accomplishment using a single number. The basic operational capability (or design adequacy, MAM, MCI) is then either degraded by other parameters, in the multiplicative equations, or weighted against other parameters, in the additive equation. Most systems today are built to accomplish multiple missions in multiple operational scenarios. Thus, using these equations, different numbers would have to be derived for each new mission and scenario, resulting in multiple measures of effectiveness. Giordano addresses the multimission scenario by suggesting a possible weighting of missions which would produce an overall system effectiveness number. The current DoDI 5000.2 warns against such weighting schemes:

> Never use schemes in which several measures of effectiveness are weighted and combined into an overall score. Weighting schemes are sometimes helpful, but they must be clearly explained in the analysis so that their results can be interpreted correctly. [Ref. 6:p. 8-12]

Thus, these equations may only be useful in providing a single-number of system effectiveness for a specific mission, and measuring overall system effectiveness would still depend on the subjective combination of several measures of effectiveness for multiple missions.

F. COMPARISON OF MODELS

1. The Multiplicative Models

These models, with the exception of the aircraft-specific Ball model, are all purported to provide a standard means of measuring system effectiveness for any system. The Giordano model addresses system effectiveness in the simplest terms, combining performance capability (P_c) with only one other attribute (P), which signifies the numerous factors which can degrade performance over time. The Marshall model, on the other hand, provides the most complex approach, adding the Mission Attainment Measure (MAM) and Survivability (S) attributes from Ball's model to the availability (Ao) and reliability (Rm) attributes of the WSEIAC, Habayeb, and OPNAVINST models. Only the Giordano model includes a discussion of measuring system effectiveness beyond a mission-specific scenario.

All of the multiplicative models present system effectiveness as some form of operational capability which is degraded over mission time. The multiplicative models use a cycle of mission accomplishment, which over time provides a measure of a system's effectiveness in accomplishing a particular mission. Each system attribute is probabilistic and through direct multiplication, combines equally with other attributes resulting in a measure of effectiveness between 0 and 1. One

difficulty in using these models is the measurement of a system's operational capability as a number between 0 and 1. Furthermore, the relevance of multiplying the key system attribute measurements into a single-number measure of effectiveness is yet unproven.

2. The Additive Models

The ASDL model presents system effectiveness for an aircraft as the result of a variety of weighted attributes. Like some of the multiplicative models, this model includes availability, survivability, and a mission capability index (operational capability). Unlike the multiplicative models, however, the additive model also includes cost and safety as attributes which lead to system effectiveness. This model relies on assigning importance coefficients to each attribute, which then combine into an overall measure of effectiveness. The additive approach will not be discussed further in this thesis.

3. A Modified Approach

In the next chapter, the author will provide a more detailed discussion of the cycle of mission accomplishment and develop a system attribute hierarchy which may be useful in relating the numerous system attributes to key attributes and hence to system effectiveness.

VII. A SYSTEM ATTRIBUTE HIERARCHY

A. INTRODUCTION

The current official guidance does not provide a hierarchy or tree for relating system measures of performance (attribute measures) to overall system effectiveness. Thus, there is no standard process by which the numerous attributes which make up a system are cohesively linked to system effectiveness. In the previous chapter, the author presented several models which link key system attributes to system effectiveness, resulting in a single-number measure of system effectiveness in accomplishing a particular mission. Although the relevance of combining the numerical values of system attributes into a single-number measure of system effectiveness is yet unproven, an understanding of the relationship between system attributes and system effectiveness is essential. Accordingly, the author will now present the beginning of a hierarchy or tree which relates many system attributes to four key attributes. Measures for each of the attributes are suggested. This new hierarchy will be closely related to the Marshall Model (see Chapter VI), where system effectiveness is defined as the result of a cycle of mission accomplishment (attributes). Any measure of system effectiveness in accomplishing a particular mission will most likely use these four key attributes. The hierarchy is proposed as a tool which might assist system engineers, analysts, and test and evaluation personnel in relating tradeoffs between the numerous system attributes to mission-level measures of effectiveness.

B. THE CYCLE OF MISSION ACCOMPLISHMENT

1. The Key System Attributes

Describing the combined effect of all attributes on overall system effectiveness (mission accomplishment) over the life of a system is quite cumbersome if stated in

terms of the separate effect of each attribute. A more useful hierarchy of attributes can be developed through an understanding of the cycle of mission accomplishment. Shown in Figure 7.1, this cycle identifies four overall key system attributes which describe overall system performance over time. For some systems, the cycle of mission accomplishment may occur only once. However, for most systems, the cycle may be repeated many times. Although the order of attribute occurrence may vary, the cycle usually begins with a system being available for use (Availability) on a given mission, continues with the system not breaking down during the mission due to malfunction (Reliability) or being killed or critically damaged by a threat (Survivability), and ends with some form of mission accomplishment (Capability).

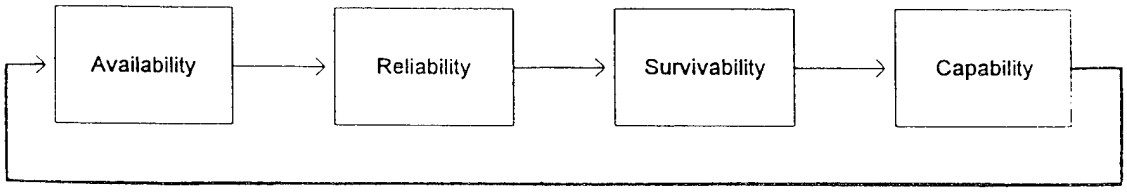

Figure 7.1. Cycle of Mission Accomplishment

2. The Key System Attributes Defined

Use of this model necessitates the following definitions, and measurements, for the given key system attributes:

a. Availability

The availability of a fielded system, called Operational Availability, defined as the probability that a system will be available for use when required. Measurements can be either [Total up time / (total up and down time)] or [# of ready systems / total # systems]. For an unfielded system, called Inherent Availability, defined as readiness in terms of inherent design characteristics. Measurement is (Mean Time Between Failure) / (Mean Time Between Failure +Mean Time To Repair).

b. Reliability

The probability that a system will perform mission essential functions for a period of time under the conditions stated in the mission profile. Measurement is $e^{(-T/\,MTBOMF)}$.

c. Survivability

The capability of a system to avoid or withstand hostile environments without suffering an abortive impairment of its ability to accomplish the designated mission. Measurement is P_s.

d. Capability

A measure of mission accomplishment (i.e., mission completion time, # of messages sent, # of enemy tanks killed) in a particular operational scenario.

3. The Importance of Time

The above model provides an overall description of key system attributes in terms of the cyclical employment of a system in its intended operational environment over time. The element of time is important, as most military missions are part of

larger operational scenarios which involve repeated system employment, at a planned utilization rate, over a specified time period. The cycle must be assessed over time, as a proper measure of overall system effectiveness must consider the time-related degradation in a system's ability to accomplish a mission. This holds true even for fire-and-forget systems such as missiles, where repeated firings are usually necessary in the overall accomplishment of a mission.

C. A PROPOSED SYSTEM ATTRIBUTE HIERARCHY

A system attribute hierarchy or tree can now be developed by expanding beyond the four key attributes of the cycle of mission accomplishment to include consideration of lower-level attributes. This hierarchy, shown in Figure 7.2, provides a method of relating tradeoffs between the numerous system attributes to overall system effectiveness.

D. CONCLUSION

Using the proposed cycle of mission accomplishment, a relationship between a system's numerous attributes and system effectiveness at the mission level is developed. This relationship is shown in the proposed system attribute hierarchy. The tree consists of four key attributes, Availability, Reliability, Survivability, and Capability, which result in system effectiveness in accomplishing a particular mission. Although the relevance of combining the four key system attribute values into an single-number system effectiveness measurement is yet unproven, the hierarchy itself provides a useful tool for understanding and conducting tradeoffs between various system attributes in arriving at an optimal level of system effectiveness.

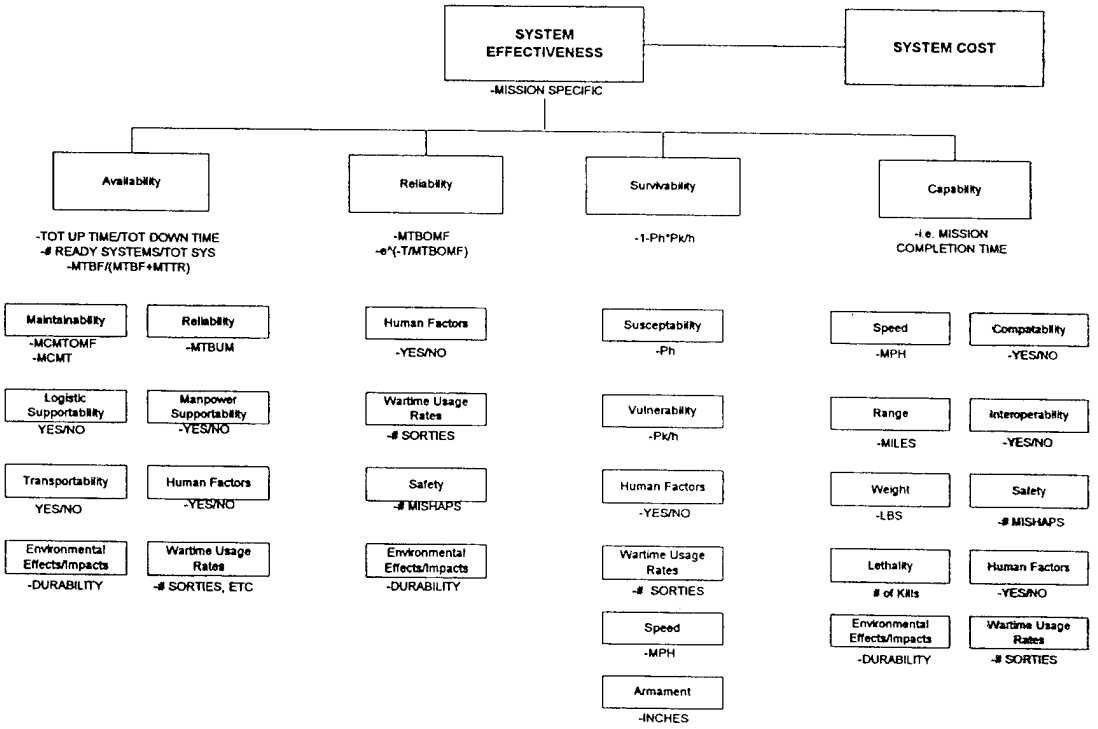

Figure 7.2. System Attribute Hierarchy

VIII. SUMMARY AND CONCLUSIONS

In the system acquisition process, the effectiveness and the cost of a system are the two key ingredients in determining system value to the military services. The effectiveness of a system is directly related to the characteristics or attributes of that system (e.g., speed, reliability, survivability). Success in system acquisition relies on (1) the early identification and successful incorporation of those system attributes that are critical to system effectiveness, and (2) the specification of numerical values for the system attributes (the system requirements) that maximizes system effectiveness at an acceptable cost.

In this thesis, the relationship between the attributes, or characteristics, of a military weapon system and system effectiveness of that system was thoroughly examined. The current guidance mandates that system effectiveness be measured in terms of engagement or battle outcomes (at the battle level). To provide a basis for linking system attributes to system effectiveness, the author provided a wide spectrum of system acquisition-related documentation which supports an additional viewpoint to the current DoDI 5000.2 - that system effectiveness should also be measured in terms of mission outcomes (at the mission level). Furthermore, in the system development and test process, the mission level provides the best means for linking system attribute measurements to system effectiveness measurement. Accordingly, the author proposed new definitions for system effectiveness and measures of effectiveness which acknowledge that system effectiveness should be measured at both the mission and battle levels.

The current DoDI 5000.2 guidance also does not provide a standard model for linking system attributes to system effectiveness. Thus, the author described several existing multiplicative and additive models which combine a few key system attribute

measurements into single-number measures of system effectiveness in accomplishing a particular mission. Finally, using a similar basis to the multiplicative models, the cycle of mission accomplishment, the author proposed a hierarchy or tree which relates many system attributes to the four key attributes, Availability, Reliability, Survivability, and Capability, and hence to system effectiveness in accomplishing a specified mission. Although the author acknowledged the need for a model relating system attributes to system effectiveness, the relevance of developing single-number measures of system effectiveness was left unproven. Ultimately, the goal of this thesis was to provide the reader with a better understanding of the relationship between system attributes and system effectiveness.

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